GreenTouch Roadmap:

Strategic Research Areas and Project Portfolio

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The GreenTouch Consortium

Editors:

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Table of Contents

I. Introduction

A major effort within the GreenTouch consortium is the development of a technology roadmap to accomplish the GreenTouch mission of delivering by 2015 the architectures, technologies and solutions, and to demonstrate key components to increase the information and communication technology (ICT) network energy efficiency by a factor 1000 compared to 2010 levels. This roadmap has four essential elements: (1) a network energy reference model and associated tools for estimating current energy trends and evaluating potential future solutions; (2) a strategic research areas (SRAs) compendium that captures the major research challenges and associated energy efficiency targets; (3) a portfolio of research projects and activities that address the strategic research areas along with an integrated and consolidated view of the overall end-to-end network architecture; and (4) a progress measurement indicator detailing how and when the research projects accomplish progress towards achieving the consortium goals.

GreenTouch has the goal to deliver the architecture, specifications and roadmap—and demonstrate key components—needed to increase network energy efficiency by a factor of 1000 from 2010 levels[4]

In order to transform the efficiency ICT networks, the GreenTouch consortium requires a clear picture of how these networks consume energy today and their potential evolution into the future [1-3]. From its conception, the GreenTouch membership has been developing network models, conventions, and tools to be used by the consortium to develop this picture and to serve as a platform to evaluate its technology innovations. These various models and tools are incorporated into the main technology reference models portion of the roadmap and detailed in the roadmap documentation (element 1 above). As new architectures and technologies are proposed within the consortium, the research portfolio is expanded and the impact of the newly proposed solutions towards the consortium goals is evaluated and captured within the roadmap. When available, various targets or reference architecture related factors are also introduced. However, many long term research endeavors begin with uncertain benefit and/or connection to the existing technologies and thus the first step is to bring focus to the critical elements and challenges. As progress is made, both the impact and potential time horizons can be introduced.

In this document, the GreenTouch consortium describes the second element of the roadmap, the main strategic research areas (SRAs) that were identified to have strong potential with respect to the main consortium objective of a 1000-fold overall network energy efficiency improvement compared to corresponding 2010 levels, while respecting adjacent technologies and related energy metrics [4]. This document also highlights the third element of the roadmap and presents the major research activities currently being investigated by the consortium members. In addition, the document also brings attention to promising research areas of critical need that require further in-depth investigations. Already some time horizons have been identified for wireline access networks and for a new mobile network architecture. Further details on timelines and technology innovations will be described in later documents in line with the overall GreenTouch mission of delivering a complete roadmap by 2015, including a network energy reference model and associated tools for estimating the current energy efficiency and current trends. Given that GreenTouch is a broad consortium that supports and encourages a wide range of efforts from many different organizations, it brings together different architectures, technologies and solutions and evaluates them objectively against the consortium objectives and metrics to obtain an overall research portfolio. As new proposals are introduced, they add to the research portfolio and the roadmap. The impact of existing research activities are continuously refined as new results are obtained or improved models and tools put to use.

The scope of the GreenTouch strategic research areas (SRAs) and its roadmap generally cover that portion of the network that is managed by the service providers or network operators. Thus, end user equipment, most home and enterprise networking equipment is excluded, unless otherwise indicated. A detailed description of the scope is provided with each section of the document describing the respective technical areas.

II. Background

ICT networks have been identified as a key element in global strategies for sustainability across society. In one case, ICT infrastructure was predicted to offset five times its own respective carbon footprint by 2020 [3]. These advantages primarily center around so called smart technologies that enable people to better monitor and thereby control energy use. Notable smart solutions include smart grids with enhanced controls on the electric power grids, smart buildings including building systems and appliances, and smart transportation control of traffic congestion. ICT enabled sustainability solutions are a central foundation for smart cities and communities.

The benefits of ICT networks depend on scalable and ubiquitous ICT network connectivity. Recent studies have indicated that network scaling will face greater technological hurdles than previously encountered [1]. Energy is central to these challenges. While Moore's Law scaling in electronics for example is expected to continue, the historical power scaling has slowed and is creating technological shifts, such as multicore processors, that are impacting network equipment. Furthermore, optical technologies have matured to the point that single fiber information capacities are approaching Shannon limited performance. This trend is forcing architectural changes in the network. Thermal densities in telecom equipment racks are running up against building-standards limits. At the same time traffic growth is still strong and the diversity of network services, applications and energy hungry capabilities continues to expand. Mobile traffic in particular has seen dramatic growth and base station energy use is becoming a significant fraction of a service provider's operating expenses. Wireline access networks and their relative contribution to energy use in the home and office are likewise increasing. While ICT networks are estimated to account for less than 1% of the global carbon footprint, this still represents levels similar to the global airline industry [3]. With near exponential traffic growth and slowing equipment efficiency improvements, network energy use is rapidly increasing. Major new technological innovations are needed to keep pace with these changes and continue network scaling into the future.

III. Services and Traffic Trends

The energy required to power a network of a given topology is strongly dependent on the nature of the services provided by that network and the volume of traffic. The GreenTouch consortium has developed a methodology for projecting a given traffic trend forward in time based upon historical growth rates and near-term bottom up forecasts. General categories of services are identified sharing certain characteristics such as latency or communication platform. While specific instances within these categories may vary widely in traffic volume over time through market adoption cycles for competing solutions, the bulk traffic will often show systematic growth behavior. The public Internet backbone is the most general example of this. It is assumed here that similar broad categories such as consumer Internet video, general web traffic, and peer to peer file transfers, will exhibit similar behavior and it is therefore reasonable to use the growth rate method to project the evolution of each category forward to the year 2020. Graphed in Figure 1 is the result of this approach for the consumer Internet traffic trend data for the mature market segment. This market segment is characterized by a similar low growth rate in the number of users and consists of Japan, Northern America, and Western Europe [1, 5]. For each category and region the most likely traffic volume and a range of possible traffic scenarios, which are intended to be used to stress and test the robustness of proposed network solutions, are formulated using data regression analyses. In Figure 1, the expected traffic scenario is denoted by the curve labeled "medium" and the extrema of the traffic scenario stress range are denoted by the curves labeled "low" and "high."

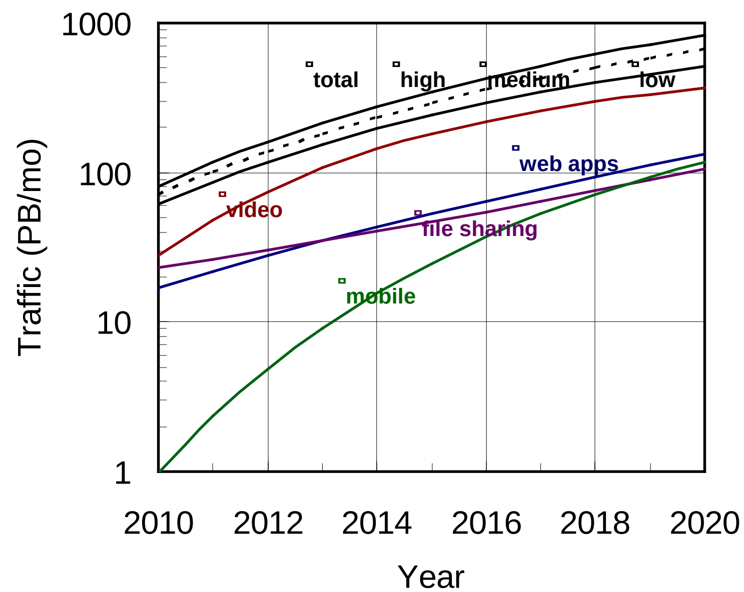


Figure 1. Consumer Internet traffic projections to 2020 by application category for the mature market segment (units: petabytes/month).). Most likely traffic levels (medium) are shown unless specified otherwise.

The traffic trends for the mature market segment (Figure 1) indicate a 10-fold traffic increase for the total traffic volume between 2010 and 2020. This multiplicative increase is lower than the corresponding global trend (15x) and the trend for the emerging markets segment (30x), as the uptake of broadband Internet is already substantial in the mature market segment. In contrast, mobile data traffic for the mature market segment is projected to increase 100-fold, reflective of the current rapid increases observed. The compound annual growth rate of mobile data traffic does, however, slow significantly over this period. Across the categories, the traffic increases for the mature market segment range from 5-fold to 100-fold over the decade. For the emerging market segment the corresponding range across the categories is 15-fold to 300-fold.

Within the GreenTouch objectives, network innovations must be designed to handle this range of traffic increase while operating at lower power such that the overall efficiency is improved by 1000-fold relative to commercial networks in 2010 for the more challenging mature market segment [4], which because of its present large but slower traffic growth rate, is more strongly dependent upon improved technological gains – as opposed to increased system loading – to improve overall network energy efficiency over the decade.

IV. Strategic Research Areas and the GreenTouch Research Portfolio

GreenTouch has identified several strategic research areas (SRAs) and challenges. From the early developments of the GreenTouch consortium, several major research themes have emerged. In this section, the major research themes and associated SRAs will be described. The section then further provides an overview of the initial portfolio of research projects and activities that have been launched within GreenTouch to address the identified SRAs.

The three major research themes that have emerged within the consortium find an application in the different network platforms, including mobile and wireless networks, wireline access networks and core optical and packet data networks. These include:

1. Multiplicity of small network elements and dynamic power management
2. Service-aware heterogeneous networks
3. Low power electronic and photonic devices

1. **Multiplicity of small network elements and dynamic power management:**

Significant network energy benefits can generally be derived from the use of a large number of small, often simplified network elements compared to those in today's networks. These benefits stem from one or both of the following advantages: (1) more efficient operation can be achieved through reducing the element size or by simplifying the elements; (2) greater adaptability or load proportionality can be achieved. The first advantage can come from reducing the thermal load, moving to lower speed devices, enhanced component integration, cooperative behavior, or specializing the functionality to the local environment. The second advantage can be derived from a combination of greater time and spatial traffic variability in the local environment as well as faster or increased power adaptation capabilities in the micro-elements. However two major challenges with this approach are:

- Avoiding an increase in energy use due to the large multiplicity of small elements,
- Managing the increased computational or communication requirements associated with coordinating and assimilating data from the individual units.

Central to dealing with the energy of large numbers of small elements is minimizing any common equipment, baseband, or overhead energy requirements. It is also crucial to only activate those small network elements that are required to support the traffic demand and the quality of service required by the underlying applications and services. Especially in light of time-varying traffic demands in the networks, dynamic power management, configuration and adaptation need to be finely tuned to achieve an energy-follows-load profile of the network elements and the network as a whole.

Examples of network architectures that take advantage of these concepts of a multiplicity of small network elements include:

a. Small cell data networks offering reduced transmission losses and adaptation to local traffic variability
b. Small antenna elements with smaller individual footprint being assembled in a large scale antenna array with cooperative beam-forming transmission
c. Single chip switching and routing elements with reduced interconnect losses handling all packet processing functionalities and being assembled in new switch and router architectures.

2. Service-aware heterogeneous networks:

The second major theme considers service-aware heterogeneous networks and energy efficiency improvements that are realized by optimizing for one or a few key service dependent network functions or capabilities. In micro-electronics, an application specific integrated circuit (ASIC) exhibits up to two orders of magnitude higher efficiency for performing complex tasks relative to a general processing unit, such as a personal computer microprocessor [6]. This is because the chip can be architected for the specific set of operations needed for the task. For ICT networks, services such as video streaming or file transfers are the equivalent of an ASIC processing task. Today's IP networks are designed to accommodate a wide range of services with very different performance objectives and requirements such as latency, security, and bandwidth, in analogy with a general processing unit. This perspective motivates energy efficiency improvements realized through two general directions:

- Optimizing around the highest volume and/or most energy consuming services,
- Providing service optimized functionality for different services within the same platform.

The first approach relies on the potential for networks to be dominated by services with specific common characteristics. The second approach is similar to building multiple overlay networks optimized for different services. The key in this case is that these heterogeneous overlay networks share a common platform and/or baseband/overhead functions to minimize the associated energy, so that the power is dominated by the service specific operation.

Examples of network architectures that take advantage of these concepts of a service-aware network include:

a. Mobile network architectures that separate the mobile signaling network from the mobile data network
b. Service dependent energy tradeoffs in mobile systems, such as delay tolerance or low transmission rates
c. Optical core network architectures designed from a service-aware perspective and that consider basic energy tradeoffs.

3. **Low power electronic and photonic devices:**
Substantial energy efficiency gains can be obtained through new designs of low power electronics and low power photonics components, as well as the tighter and more efficient integration of opto-electronic circuits.

Examples of technologies include:

a. Beyond Moore's Law, adiabatic switching and fault tolerant computing
b. Optical interconnect technologies
c. Silicon photonic integration

Strategic Research Areas (SRAs)

Within the scope of the major research themes outlined above, the GreenTouch consortium has identified several promising strategic research areas (SRAs). Within each of the key technical domains in access and core networks the major research challenges and focus areas are identified in Figure 2. Each of these SRAs in mobile, wireline and core networks is described in more detail within the respective technology sections below. The main cross-domain challenges that provide benefit across multiple platforms are also identified. Note that in some cases technology, component, or algorithmic solutions are identified, whereas in other cases areas of study are identified with potential to lead to new understanding that can impact energy efficient solutions, e.g. architectural trade-offs considering fundamental energy and technology constraints in wireline access systems.

Three areas are identified under the cross-platform category. (1) Energy efficient electronic communication processing elements identifies processing units optimized for communication equipment. Examples in use today are ternary content addressable memory (TCAM) or forward error correction (FEC) coding electronics. Technologies that might become important include fault tolerant techniques or two ways: first as the basic interface technology for communication at distances longer than a few meters and second as a short reach interconnection technology with potential to address energy scaling challenges for chip to chip and even on chip interconnect electronics. (3) Moving beyond the current layered network structure requires simulation tools that can accurately model traffic dynamics and equipment behavior operating within and across these layers.

Mobile Communications

- Network and system technologies that enable separate signaling and data communication for efficient, high capacity mobility
- Deployment of small cells and smart network management
- Large scale cooperative antenna based systems
- Wireless channel energy and performance tradeoffs

Wireline Access

- Capacity and energy efficient protocols and algorithms
- Home gateway virtualization techniques
- Architectural tradeoffs considering fundamental energy and technology constraints
- Low power micro-electronics and photonic components

Core Networks

- Dynamic, power adaptive networking technologies
- Energy-centric protocols and network layering/cross-layer functionality
- End-to-end and service aware architectures and technologies

Cross Domain

- Energy efficient electronic communication processing
- Energy efficient optical transceiver technologies
- Cross-layer network simulation tools

Figure 2. Major strategic research areas by network platform.

Research Project Portfolio

The SRAs described in this document define activities that contribute to a vision for future networks that the GreenTouch consortium is building toward. The consortium has organized projects within each of these strategic research areas and seeks to partner with other organizations and to engage new members to further develop the research base within these research areas. In this section of the document, we provide a brief introduction to some of current research projects within GreenTouch. Additional information on these projects and research activities is provided online at www.greentouch.org and in [4].

1. Mobile communications:
    a. Large Scale Antenna Systems (LSAS)
    b. Beyond Cellular Green Generation (BCG^2)
    c. Green Transmission Technologies (GTT)

2. Wireline access:
    a. Bit Interleaving Passive Optical Networks (Bi-PON)
    b. Transparent Client Premises Equipment (CPE)
    c. Long-Reach PON Architectures
    d. Virtual Home Gateway (VHG)
    e. Low Energy Access Network Architectures (LEAN)

3. Core networks:
    a. Service Energy Aware Sustainable Optical Networks (SEASON)
    b. Single Chip Router Linecard with Silicon Photonic Interconnects (SCORPION)
    c. Content Distribution and Clouds for Service Delivery (CROCODILE)
    d. End to End Optimal Resource Allocation (OPERA)
    e. Zero Buffer Router Architectures (ZeBRA)
    f. Router Power Measurement (REPTILE)
    g. Switching and Transmission (STAR)
    h. Energy Efficient High Capacity Optical Orthogonal Frequency Division Multiplexed Signal Transmission (EFI-COST)
    i. Highly Adaptive Layer for Mesh On-Off Optical Networks (HALF MOON)
    j. Dynamic Reconfiguration Aware Green Optical Networks (DRAGON)

Through 2015, the GreenTouch consortium is working to validate the potential of these technologies and to identify new technologies or architectures to achieve its goals. The scope of research for this end to end view is quite broad and GreenTouch seeks to foster and promote new programs that build toward this vision, and to partner with other organizations, funding agencies, and investors in order to bring this vision to fruition. Figure 3 illustrates a potential end-to-end network architecture where the activities in the different strategic research areas come together to achieve the overall network energy efficiency improvements. The following sections on mobile communication (section V), wireline access (section VI) and core networks (section VII) describe the specific research areas and associated research challenges in more detail. Additional information is also provided on the projects in the current portfolio.

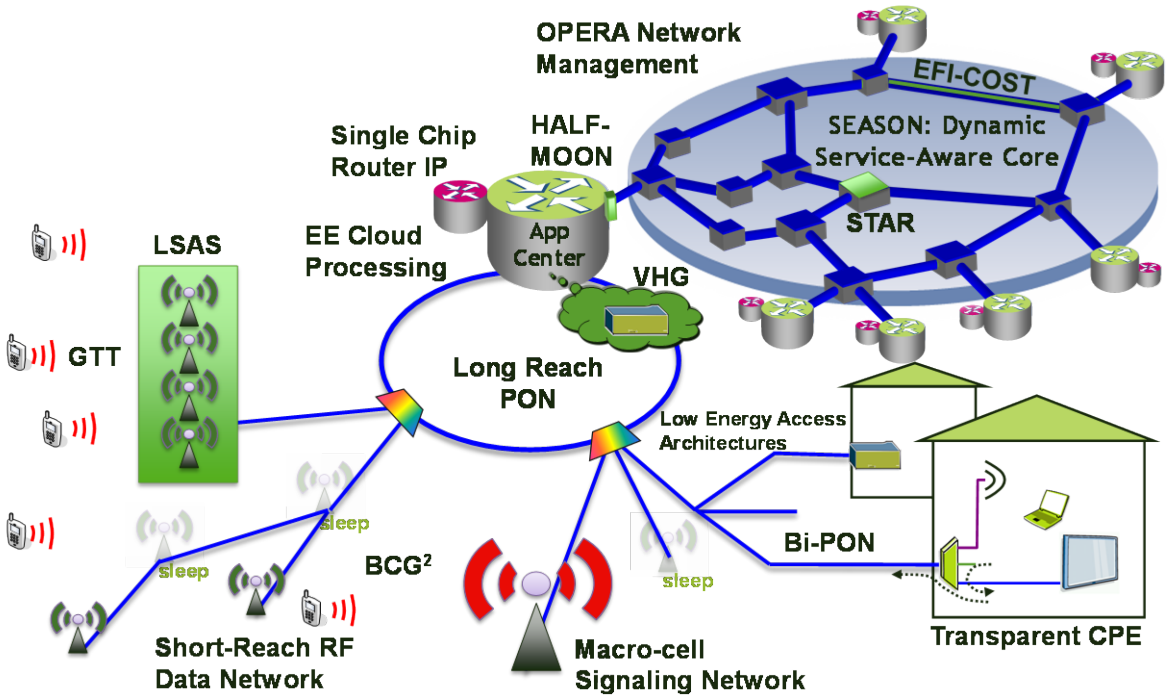


Figure 3. A unified network vision for future energy efficient networks.

V. Mobile Communications

In mobile systems, 80% of the power goes into base stations (BTS) and therefore they form the focus of energy efficiency measures. In a base station, a certain system level power needs to be provided (from the electric power grid for example) in order to achieve a target transmitted radio frequency (RF) power. Furthermore for a given transmitted RF power, one can service a given amount of traffic over the cell or distribution area. From this perspective, efficiency measures can be divided into two general categories: input/output (system level power from the electric grid) base station efficiency and the RF channel efficiency. These two dimensions are illustrated in Figure 4 [7].

The efficiency gains in each area can be further broken down into system and network improvements. For the system level, input/output efficiency measures include component and processing power improvements, sleep mode operation, and transmitter adaptation. For the RF channel, improvements are centered around air interface transmission technologies and cooperative remote radio modules. At the network level gains come from more energy aware deployment strategies combined with agile and intelligent management of the available and currently needed network capacity. Adaptation of network capacity can be achieved by dynamic configuration of network nodes up to turning on and off entire base-stations or antenna units. Another research direction centers on energy efficient wireless access network deployment schemes (i.e. centralized radio access networks), which could potentially become the common network platform. In the next sections, the main architectures and specific research challenges and projects are highlighted.

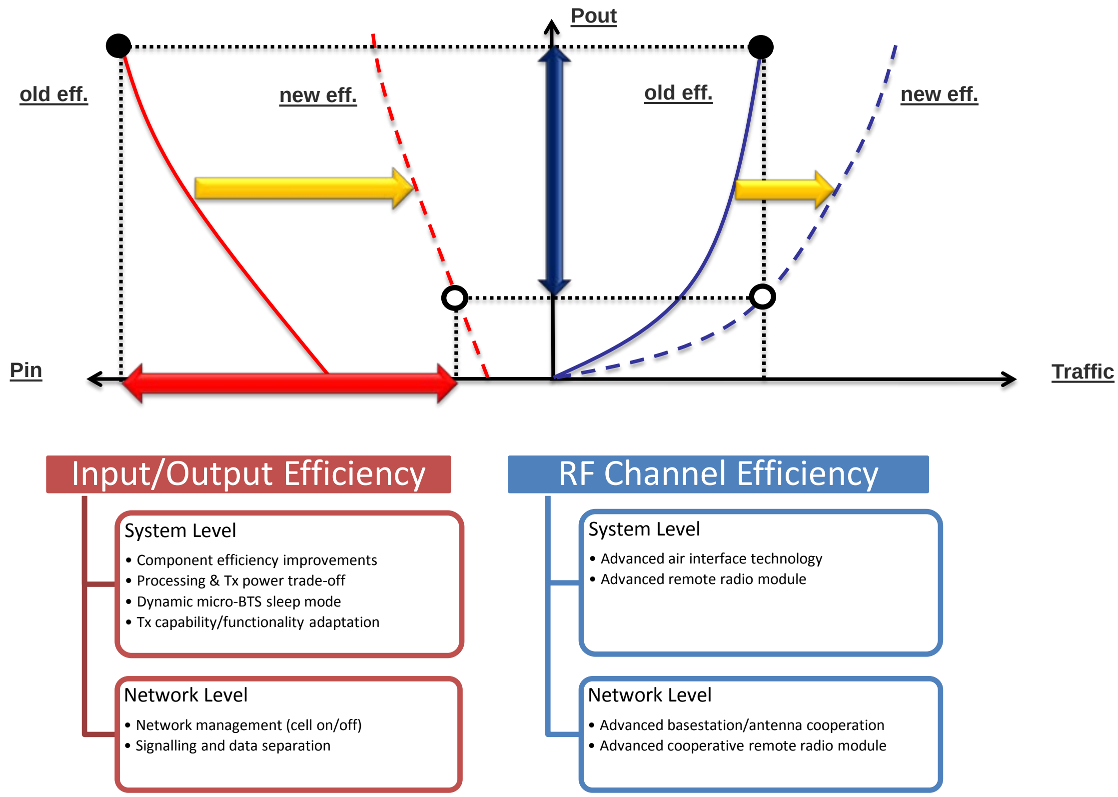


Figure 4. Different axes of mobile energy efficiency gains.

Large Scale Antenna Systems Architecture (LSAS)

A first GreenTouch project for mobile communications was a large-scale MIMO system demonstration. The experiment entailed reverse-link transmission for a single-antenna “terminal” to a receive-only antenna array comprising between one and sixteen active elements, each element in turn comprising four co-phased patch antennas. The array performed maximum-ratio combining based on channel estimates derived from reverse-link pilots. The experiment demonstrated that, for every doubling of the number of antennas, the radiated power of the terminal could be reduced by a factor-of-two without degrading the quality of the processed signal. It also showed this procedure is fully adaptive to the propagation environment. The principle of TDD reciprocity permits the conclusion that similar improvements in radiated power efficiency can be realized in forward-link data transmission. The Large-Scale Antenna Systems (LSAS) architecture seeks to improve wireless energy efficiency through a combination of radiated power reduction and increased throughput (spectral efficiency). Figure 5 shows what could theoretically be done with M = 100 to 800 antennas using large scale antenna systems (solid blue curves) versus what could be done with a single antenna operated conventionally (red asterisk).

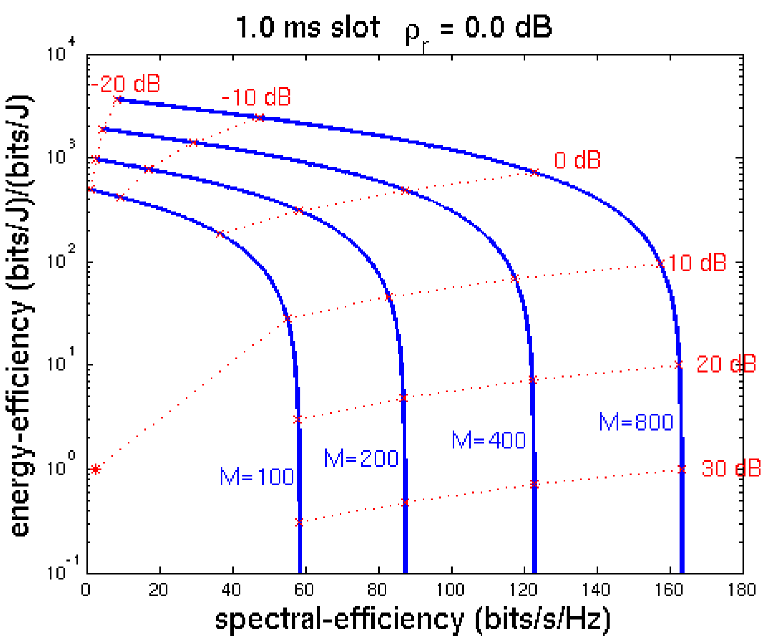


Figure 5. Input/output radiated signal energy efficiency for a given spectral efficiency with LSAS using M antennas versus a single conventional antenna. Contours of constant radiated power shown in red. Coherence interval (slot) is 1 ms. ρ_r is the reverse link expected SNR. Asterisk shows a single antenna reference.

To realize the LSAS architecture one must address both problems that concern reduction to practice (e.g. signal processing algorithms; acquisition at low radiated power levels; quantization effects) as well as fundamental problems (e.g. how to deploy hundreds or thousands of antennas; how to reduce overall internal power consumption commensurate with reducing radiated power) [8, 9].

Architecture and Deployment. A typical macro-cell cannot accommodate hundreds of antennas. LSAS research must consider new deployment scenarios and their architectures, such as for example massively co-located antennas, spatially distributed antennas, or a hybrid solution (see Figure 6).

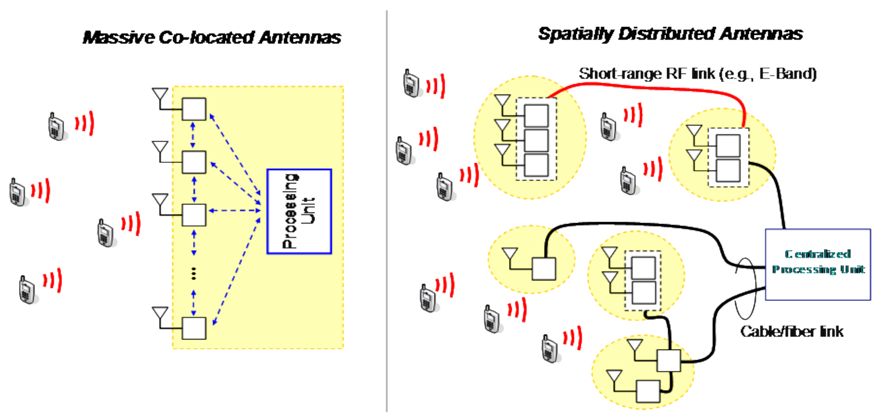


Figure 6. LSAS deployment strategies: massive co-located antennas versus spatially distributed antennas.

Co-located antennas reduce the energy expenditure and overall inter-cell interference. A distributed solution exploits the multi-cell processing paradigm for interference mitigation by progressively breaking the concept of a cellular system when the antenna density increases. To enable centralized processing, each antenna must be remotely deployed to extend coverage while preserving the benefits of a co-located antenna system. Hardware and software partitioning between central and remote antenna units plays a crucial role in reducing radiated and processing energy expenditure. The femto cell paradigm, when framed into the distributed antenna architecture, would have two inherent advantages:

- Energy expenditure reduction for home equipment and for the delivered information bit; interference mitigation is achieved by coordinating clusters of antennas.
- Radio coverage extension with meaningful reduction of the radiated power by a conventional deployment of large cells.

Backhauling is part of all cooperative MIMO schemes that involve massive antenna deployments and needs to be considered in a complete analysis of energy use.

Algorithms and Simulation. Testbed end-to-end system-level simulations are required to evaluate system performance, develop practical signal processing algorithms, and assess their performance. Required simulation studies should address channel estimation and A/D conversion resolution.

Power Modeling and Control. Power models are needed to enable accurate assessments of power consumption for various deployments, architectures, and approaches to signal processing. Power modeling activities are crucial to consider the gain in total output power, and the increased digital and analog signal processing needed to support more antennas. Models need to scale to many input parameters, including the number of antennas and other parameters described in Figure 7.

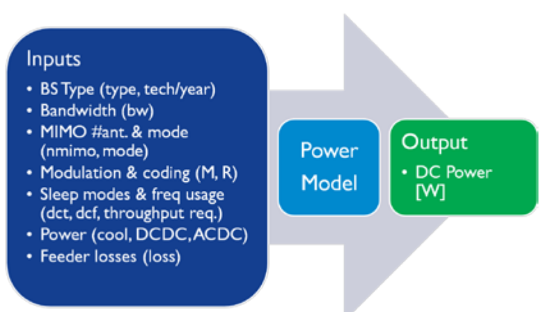


Figure 7. Input parameters for power modeling a base station architecture.

Depending on the selected parameter set, the different power contributors will scale in some way – constant power for some, linear for others, possibly quadratic or cubic for some functional blocks in multiple-antenna processing. This description enables calculation of the total required power for multiple configurations.

The research challenges and focus areas for the LSAS architecture can be organized into three main categories: experimental research in large scale antenna systems, algorithms, protocols, and system design, and enabling resources in the form of quantitative models.

LSAS Research Challenges and Focus Areas

Experimental Studies

- Deployment scenarios
- Propagation studies
- Efficient baseband processing systems, including A/D - D/A hardware, RF signal chain, error-correction
- Overall system engineering

Algorithms/Protocols/System Design

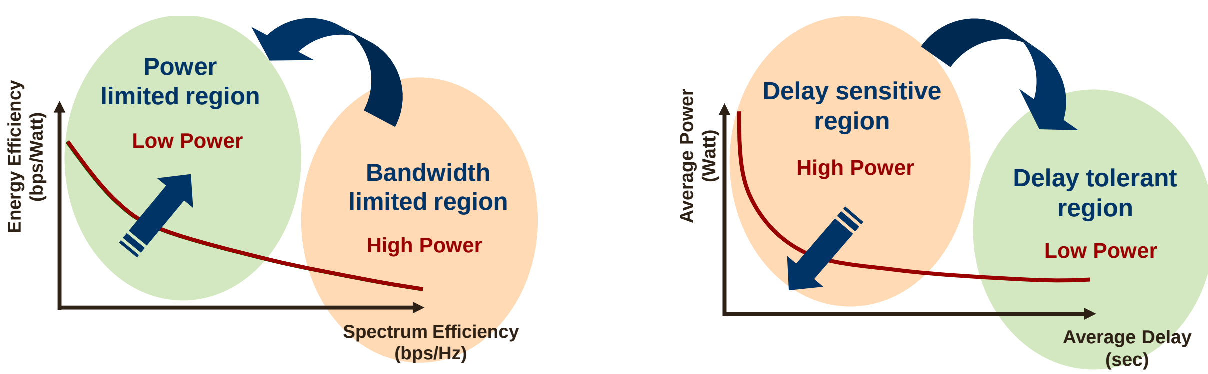
- Reliable acquisition algorithms for the low power regime including synchronization, timing recovery, and handshaking
- Terminal service scheduling

Enabling Resources

- Quantitative models for LSAS trade-off on performance & power amplifier nonlinearity and efficiency
- Quantitative models for LSAS trade-off on performance and digitization resolution
- Extension of performance models to non-cellular deployments and distributed systems
- LSAS traffic models

Green Transmission Technologies (GTT)

Green Transmission Technologies (GTT) describes a set of energy efficient transmission design schemes, radio resource management strategies, and signal processing algorithms based on the fundamental tradeoffs in wireless communications.



(a) (b)

Figure 8. Research directions related to key energy trade-offs for mobile systems: (a) low power by operating in the low spectral efficiency, power limited region; (b) exploiting delay tolerant services to achieve lower power.

The improvement of energy efficiency and the reduction of energy use are usually associated with a cost in other operational metrics. This means that the energy efficiency of the system will involve tradeoffs. The key issue is to determine an acceptable tradeoff of key system parameters while maintaining satisfactory network service. Shannon's groundbreaking work on reliable communication over noisy channels showed that higher bandwidth leads to lower transmitted power for the same data rate [24]. It also suggests the benefit of transmitting a packet over a longer period of time to save transmitter energy. GTT related activities should investigate ways to improve the system energy efficiency based on tradeoffs between spectral efficiency (SE) and energy efficiency (EE), and service delay (DL) and power (PW) consumption. Figure 8 illustrates opportunities for energy saving strategies in mobile systems that exploit tradeoffs between these quantities.

Tradeoffs in practical systems are far more complicated than the point-to-point Gaussian channel common in information theory. One reason pertains to the processing power consumption in both the baseband unit and the radio frequency unit, which makes the actual tradeoff curves counter intuitive. The literature provides no data for tradeoffs in multi-user, multi-cell scenarios. For service DL-PW tradeoffs, their characterization needs a complex combination of information theory and queuing theory; for SE-EE tradeoffs, when the bandwidth is very high or the transmission rate is very low, new signal processing algorithms may be needed in these new operating regions. Progress is needed in describing these tradeoffs with more precision, resulting in more energy efficient PHY/MAC/Network design. The research challenges and focus areas for GTT can be grouped into algorithms, protocols, and system design areas and enabling resources.

GTT Research Challenges and Focus Areas

Algorithms/Protocols/System Design	Enabling Resources
• PHY function design in the low signal to noise ratio region • Very low rate coding and algorithms for physical layer functions at very low SINRs • Complex resource sharing algorithms in multi-user environments • Interference mitigation/coordination in the low spectral efficiency regime	• Methods for acquiring additional bandwidth, including opportunistic and dynamic spectrum access as well as regulatory measures to release or re-partition spectrum • Accurate models for scalable processing including both baseband and RF components and models that capture the bandwidth dependence • Models for the impact of impairments in synchronization, channel estimation, etc. on the power/bandwidth trade-off • Models for the interference impact on the power/bandwidth trade-off • New hardware designs for operation at low signal-to-noise ratios

Beyond Cellular Green Generation Architecture (BCG^2)

The access technology for mobile networks is responsible for more than 80% of their energy use. Access also is the most critical part of the network for capacity planning, which usually accounts for peak traffic conditions. A common approach for reducing energy use considers the dynamic management of network access devices in order to switch some of them off during low traffic conditions.

However, the current cellular architecture used for wireless access networks severely limits energy management strategies for reducing energy use. The roadblock is a presumption that full cellular coverage of a service area requires user terminals to access the network at any time and at any location of the geographical area. To guarantee full coverage, many access devices cannot be turned off – even if no active users are in the cell. This becomes more problematic with micro cellular layouts because all base stations are essential for full coverage.

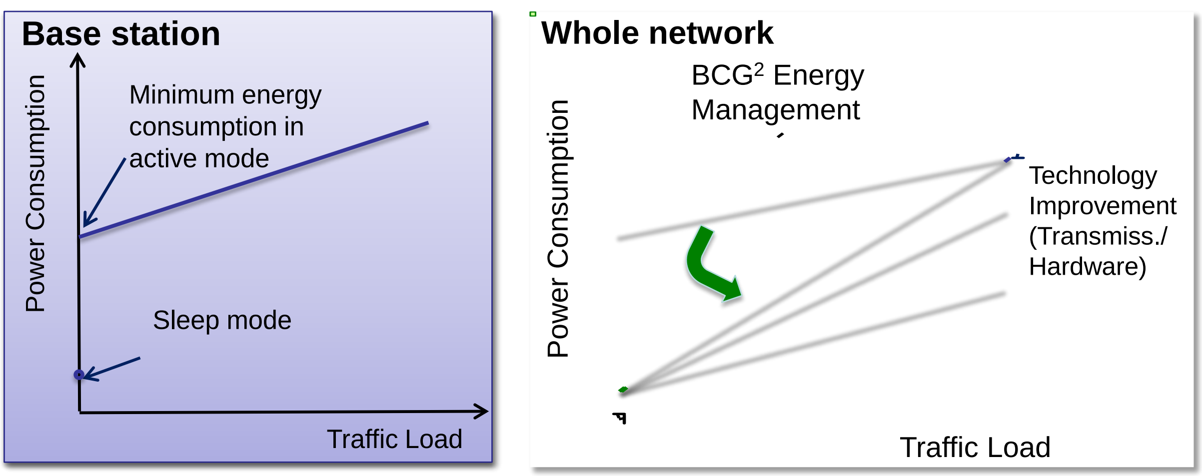


Figure 9. BCG^2 architecture enables power proportional operation at the network level, which can then take further benefit of transmission and hardware related improvements.

Beyond Cellular Green Generation (BCG^2) architecture [10] proposes to overcome these limits by going beyond the traditional cellular architecture with a complete separation of signaling and data networks. The signaling network will provide continuous and full coverage with highly efficient macro base stations, which enable communication services at any time and at any location of the service area. Portions of the data network will be activated on demand in order to minimize energy cost. Several heterogeneous data networks should be used and managed by the same signaling infrastructure. This strategy enables load proportional energy use across the entire network despite a large active mode energy requirement for each base station (see Figure 9). Further benefit can be derived from active mode hardware and transmission efficiency improvements.

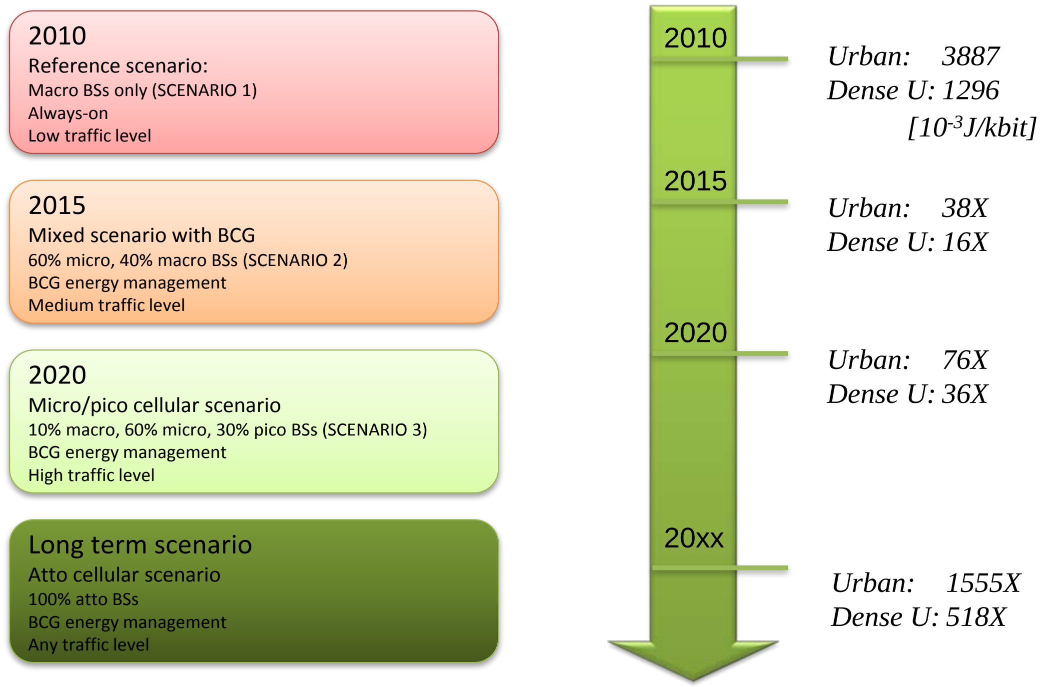


Figure 10. Gain estimation of the BCG^2 architecture considering different network scenarios.

Based on an initial analysis, Figure 10 shows a timeline noting theoretical upper bounds on potential gains in energy per bit for different network layouts and traffic levels. The network layouts include dense urban and urban scenarios. Note that these architectural benefits can be combined with other device and system efficiency improvements to potentially yield larger efficiency benefits. The BCG^2 architecture yields a wide range of challenging research problems which can be organized into experimental studies; algorithms, protocols, and system design; and enabling resources.

BCG^2 Architecture Research Challenges and Focus Areas

Experimental Studies	Algorithms/Protocols/System Design	Enabling Resources
• Implementation of low power optimized mobile data systems • Implementation of low power optimized mobile signaling system demonstrating the coordination of heterogeneous data networks • Efficient baseband processing systems, including A/D - D/A hardware, RF signal chain, error-correction	• Energy aware resource selection and activation algorithms • Algorithms and protocols to manage the interworking between the signaling network and heterogeneous data networks	• Quantitative analysis of the fundamental energy bounds for separate signaling and data mobile networks • New energy efficient mobile architecture optimized for signaling

VI. Wireline Access

About 90% of energy in today's wireline networks, which consist of core, metro and access, is consumed in the access network, with more than 10W per user being dissipated mostly by customer premises equipment (CPE) [1]. The estimated energy needed to provide network access to e.g. 100 million households in a country like the U.S. amounts to 10 TWh, which is equivalent to the emission of 7 million tons of CO_2 per year (assuming 0.7 kg/kWh) or roughly the equivalent of two coal-fired power plants. In addition to the carbon footprint issue, power consumption in access systems has historically represented a problem for network operators due to the cost of power supplies in remote units, heat dissipation in high density access nodes of the central offices and requirements for back-up battery capacity for lifeline service support during periods of power outage. The current engineering approaches to minimizing the power consumption, such as ASIC integration, migration to smaller scale CMOS technologies, and efficient cooling, will not be sufficient to keep the energy use and CO_2 emission at the current level considering the multiplicative growth of traffic in the future. The need for dramatic improvement in energy efficiency will mandate disruptive changes in the implementation of access networks.

The research areas identified for wireline access networks are expected to lead to the deployment of access networks featuring a more than 10 times lower power consumption per user and 10 times higher bit rates, for a 2020 reference case, compared to the 2010 state-of-the-art wireline access networks. The resulting energy efficiency per bit is therefore expected to be improved by more than a factor of 100.

Wireline access innovations are developed starting from a baseline architecture that is a fibre-to-the-home (FTTH) network using a gigabit passive optical network (GPON), as well as the recently standardized ten gigabit capable passive optical network (XGPON1) (see Figure 11). It is acknowledged that for the IEEE variants, EPON and 10GEPON, the power consumption levels are very similar and hence the same conclusions for the roadmap are valid. Other FTTX architectures with digital subscriber line (DSL) or hybrid fibre coax (HFC) are widely deployed, but FTTH is used as a starting point because it already is the most energy-efficient wireline access technology in commercial use today.

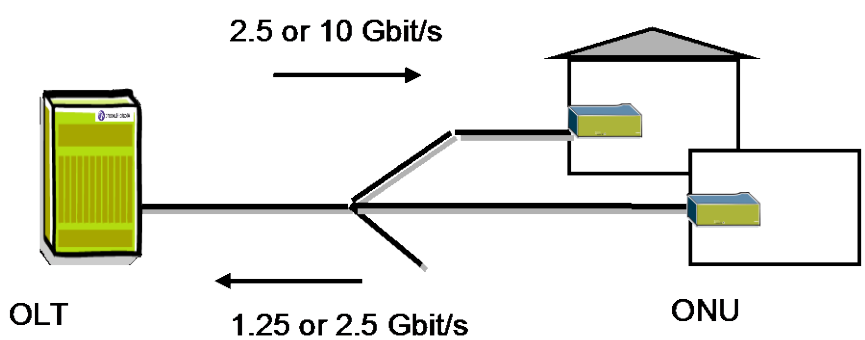


Figure 11. Wireline access baseline architecture consisting of GPON or XGPON1.

Energy Efficient Protocols and Algorithms

Sleep modes are an important concept to reduce the average power consumption of a CPE, because the CPE is not always used at the maximum throughput capacity it is designed for and hence idling for a large part of the time. A coarse sleep mode method is hibernation at times of the day or night that the subscriber is not connected. A next level of sleep mode is power shedding of functional blocks (e.g. of a specific LAN interface) that are not in use and only turned on when a session is established. These types of sleep modes are already technically feasible today and help to lower the energy consumption averaged over longer periods of time. Recent standards (ITU-T G.987.3) [11] have defined sleep cycles on XGPON over a time scale of tens of milliseconds and allow for power savings while communication sessions are active. Energy Efficient Ethernet (IEEE 802.3az) achieves similar savings on the wired LAN interface.

Bit Interleaving PON is a new time division multiplexing (TDM) transfer protocol that reduces the power consumption of the PON digital part for the downstream by almost an order of magnitude [12]. In a conventional packet based PON system, every optical network unit (ONU) processes all downstream data until it is able to extract the incoming packets destined for the local area network and drop the rest of the data. Much power is consumed in the processing of this high throughput data (e.g. 10 Gbit/s in XGPON). A new concept of bit interleaving allows for selecting the relevant bits immediately after the clock and data recovery functions. Further processing is done at the user rate instead of the aggregate line rate, which results in significant power savings. Bit Interleaving does not apply to upstream. Upstream burst mode transmission as in a conventional PON is used, which is already energy efficient because of its load proportionality.

Energy Efficient Access System Design

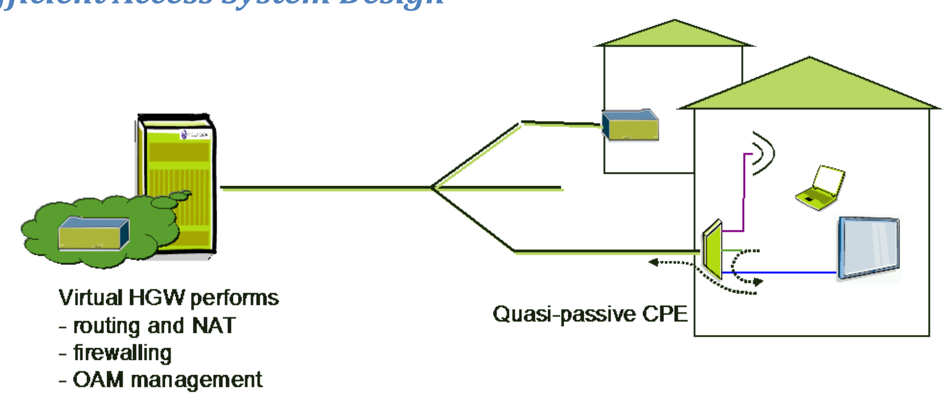


Figure 12. Architecture with virtual home gateways and transparent client premises equipment.

Virtual Home Gateway (VHG) runs the typical home gateway functions, such as routing, OAM (operations, administration, and maintenance), network address translation (NAT) and security, on a central server in the network instead of a processor on the CPE (see Figure 12). Unlike the short sleep periods applied to the data transfer functions in a CPE, it is more difficult to apply aggressive sleep cycles on the order of milliseconds on a CPU and hence, the CPU typically remains powered on in a conventional CPE. Thanks to virtualization, the CPU in the CPE can be reduced or even eliminated, while the power at the server is more efficiently used by time sharing a single processor on a server by up to a thousand subscribers. A preliminary estimate has shown a factor 10 reduction of the processing power, which is now consumed in the network. Further research is required to obtain a more accurate estimate of the power savings. Other reasons for an operator to use VHG on a central server rather than on distributed devices are simplified operation and maintenance and faster upgrade to new services that require more processing than available on CPE's deployed in the field.

Transparent CPE is a disruptive concept that provides a completely passive connectivity between the first mile and the home network [13]. The functions of conventional CPE can be moved to a server in the network by the virtual home gateway (VHG) concept described above. With the emergence of simple connectorisation and flexible bend single mode fiber for in-house wiring, it will be conceivable to have an optically transparent link to the access network. The actual implementation for example with wavelength division multiplexing (WDM) or passive splitting is still a subject of active research. It is also acknowledged that there will not be a single mode fiber to every device in the home. We anticipate a cut-through connectivity via single mode fiber to high bandwidth devices (e.g. TV or multimedia terminals), while maintaining a wireless LAN for low bandwidth devices (e.g. sensors) and mobility in the home. This concept also requires a new passive demarcation between the home and the provider network, as well as solutions for the OAM of the respective networks in the absence of an active network element between them. The concept basically eliminates most of the power related to the wireline LAN interfaces on the CPE. It is a disruptive, high risk direction given the assumption of single mode fiber in the home.

Long reach access architectures reduce the number of hops in the access and aggregation network. A SuperPON with a split of about 1:512-2048 and a range of 100 km allows for bypassing the local exchange. Although the optical line termination (OLT) function is not eliminated, but performed deeper in the network to the edge location, some electronic processing for aggregation and regeneration of data could be removed at the expense of additional power needed to achieve the reach extension. The estimated net saving is about 50% on the network side.

Optical multiplexing architectures deserve further evaluation in search of the most energy efficient solution. In addition to the baseline TDM-PON architecture, we consider Point-to-Point as conceptually the most efficient solution for an access network [14], as well as TDM, WDM, orthogonal frequency division multiplexing (OFDM) and hybrid combinations, as ways to reduce the fiber count. Each of the architectures however may have its own limitations in terms of deployment. Different innovations need to be investigated in parallel to make the respective architecture an energy efficient solution.

Energy Efficient Hardware and Component Concepts

Energy Efficient Hardware design (EE HW) refers to engineering optimizations. A first optimization includes reduced transfers of data across I/O of ASICs thanks to further integration, new interconnect techniques like 3D-stacking, and a critical review of required memory accesses. A second optimization is the use of clock gating of parts of an ASIC that are not in use. A third innovation is a new burst mode transmitter design in the ONU that allows for saving power during silent times when no upstream data is sent on a PON. Other methods to be considered are dynamic voltage and frequency scaling (DVFS), which allows for scaling power consumption with the clock speed and get additional savings from reducing the supply voltage accordingly, and asynchronous design, in which transistors only consume power when they perform a useful operation.

Low power optics and electronics innovations are being investigated in various research programs (e.g. Semiconductor Research Council) and may see commercial exploitation towards the end of the decade. The challenge for GreenTouch is to evaluate their use and potential efficiency gains in access network systems. Among the many concepts, fault tolerant data transfer and adiabatic switching are realistic in this time frame, because they are feasible with state of the art CMOS manufacturing technologies. Quantum dot automata and other concepts are still farther out. We expect a factor of three in energy efficiency gain for a practical implementation of low power electronics concepts, even though higher gains have been reported in the literature. At the same time more efficient lasers and receivers, which specifically exploit the lower rate and other access requirements to lower power consumption, can be expected for which we assume a gain of a factor of two in energy efficiency.

Wireline Access Research Challenges and Focus Areas

Algorithms and Protocols	System Design	Hardware and Component Concepts
•Sleep modes •Energy and capacity efficient protocols (e.g. Bit-Interleaving PON protocol)	•Home gateway virtualization •Transparent CPE •Long-reach PON •Optical multiplexing architectures	•Energy efficient hardware design •Low power micro-electronics •Low power optical access transceivers

VII. Core Networks

The core network comprises elements of both the underlying optical systems and the higher layer routing, switching and networking infrastructure. The GreenTouch consortium is investigating different architectural directions including (1) energy-centric advances for the traditional IP over WDM network architectures (Energy-Centric IP Network Architecture) and (2) a new energy-optimized clean-slate network architecture focused on delivering services and applications in the most energy efficient way (Service Energy Aware Sustainable Optical Networks Architecture).

Energy-Centric IP Network Architecture

Based on historical trends, up to the year 2000, the router capacity has been increasing by a factor 2x every 18 months and the corresponding energy per routed bit has been decreasing at a rate of 30-40% per year. More recently it has been noticed that the single rack router capacity growth has been slowing down and the energy per routed bit has only been decreasing at a rate of 10-15% per year [15]. At the same time, traffic continues to grow at a rate of about 20-40% per year, leading to a potential increase of the overall traffic by a factor 10-30x over the next ten years and approaching a factor of 1000x over the next twenty years [1]. As a result, a significant energy gap is widening between the traffic growth and the equipment efficiency evolution, given business as usual trends.

There are several technical limitations and factors contributing to the slow-down of the reduction of the energy per routed bit over the past decade. These include among others a slow-down of the reduction in dynamic power dissipation as a function of the CMOS feature size; this is generally viewed as a consequence of complications in continued Moore's Law scaling [16-19]. In addition, it is anticipated that the interconnect power will dominate the overall power consumption of future line-cards and routers. In fact, already today, it is not uncommon to find more than ten processor chips on a single line-card and any given packet has to be transmitted to and then processed by all of these chips. A significant power consumption is associated with the on-off transition to the respective chips and the interconnects themselves. Further, about 65% of the total power consumption of a router is associated with layer 3 packet processing functions. The associated protocols have not been defined and optimized for energy efficiency and can be improved through elimination of redundant and unnecessary processing, especially if one is afforded the freedom to redefine standards and legacy service needs. Finally, network elements and indeed the network as a whole generally have not been designed for energy efficiency. In particular, very often the power consumption is not proportional to the processed traffic load, but is rather constant and independent of the traffic with a substantial overhead (up to 70-90% of the maximum power consumption) even without any traffic at all [20].

In order to achieve significant gains in networking energy efficiency, we have to take a complete end to end perspective and include all aspects of the communication system. Broadly speaking, the different technologies can be categorized in five largely independent topical areas. We provide some potential research directions for each of these categories:

1. Chip-level components and devices:

Substantial energy efficiency gains can be obtained through new designs of low power electronics and low power photonics components, as well as the tighter and more efficient integration of opto-electronic integrated circuits.

Efficiency gains for IP networks require new technologies such as silicon-photonic interconnects to reduce the power consumption in the interconnect structure by bringing the optical interface as close as possible to the electronic processing. From the serializer / deserializer (Serdes) on the transmit side to the receive side, efficiencies should approach fJ/bit for both interconnects and core transmission. Furthermore, using such technologies one might realize line-card functionality on a single chip that can handle all the router / packet processing that is currently spread over multiple chips. Hence, the overall power consumption is reduced (1) by employing fewer chips to perform equivalent functionalities to today’s line-cards and (2) by leveraging silicon photonic interconnects to minimize the interconnect power consumption during the on-off chip transition. A goal should be the hybrid integration of silicon photonics with CMOS in a single chip. The silicon photonic components will provide the fiber couplers, multiplexers and filters and the modulators and detectors. The CMOS component of the chip will provide the modulator drivers and receiver as well as the logic to implement functionalities of the chip (e.g. FPGA, packet processor, or switch).

2. Network element architectures:

New technologies and physical layer components should be integrated in novel energy efficient network element (i.e. routers, switches, cross-connects, etc) architectures and designs.

Routing and switching line cards with single or few chip architectures with integrated packet processing functionalities can lead to innovative router architecture designs. Such new designs could include flexible and massively scalable router hardware architectures with multiple parallel packet processing chips and dynamic reconfiguration and load balancing capabilities.

The integration of active and passive elements can replace current inefficient switch designs and lead to new optimized low-power photonic switches and hybrid photonic and electronic switches. In return such new photonic-enhanced switch designs can form the basis for novel network architectures and network management and control paradigms.

An important element in optimizing the power consumption of network equipment is a deep understanding of the current power consumption and knowledge of how the power consumption is distributed across the different modules, sub-systems and components of the network element in question. It is equally important to have detailed understanding of how the power consumption is affected by the traffic volume, the traffic variability, the number of connections, the packet sizes, etc. Research efforts should be dedicated to detailed power measurements and power consumption modeling that can then be used in real-time management and control of the network elements.

3. Network architectures and topologies:

New network architectures and topologies need to be investigated that optimize the total power consumption in the network, as well as the total cost of ownership of future networks (including the capital and the operational expenses). These network designs provide the most energy-efficient IP over WDM network architecture by optimizing the trade-off between optical and electronic packet transport and processing. Different network topologies need to be considered, including a completely centralized, star-like network topology, a fully meshed network topology and hierarchical network topologies. Efficient topologies need to be determined as a function of the network size, the traffic load and the traffic matrix, the underlying capabilities (e.g. the optical channel capacity or the router port capacity) and the power consumption of the hardware. It is anticipated that higher energy savings can be obtained in larger networks with more alternate paths and higher connectivity (such as those provided for example by large photonic switches).

Extensions of current routing protocols to incorporate energy efficiency of the selected paths also need to be considered. Initial research has been conducted to assess the opportunities of joint routing and scheduling in the network based on time-varying traffic demands and power consumption models of the network equipment. This initial research needs to be extended to derive real-time algorithms and protocols that can be deployed in future networks. The power profiles of new network components and elements also need to be taken into account.

Finally network architectures should also consider the integration of data storage and caching to arrive at the overall end-to-end optimal solution for content delivery. It is anticipated that replicating and storing popular content in the network can yield energy efficiency gains, as well as improved throughput and end-user experience. Content caching and delivery strategies have been developed but so far have not necessarily been optimized for energy efficiency. Extensions of the current frameworks for content distribution networks (CDN) and information centric networks (ICN) need to be investigated that provide the energy-optimal selection of cached content, the cache locations and refresh policies, taking into account the total power consumption for transport, content processing and storage.

4. Dynamic management of resources:

Networks are very often dimensioned for peak traffic load and worst case scenarios. While it is important to account for traffic variability, network management should also take into account the dynamic nature of traffic and allocate resources throughout the network to match the traffic load. An important balance needs to be struck between allocating too many resources – and thereby wasting resources and unnecessarily increasing the network power consumption – and not allocating enough resources – and thereby degrading quality of experience for the end-users and violating service level agreements. This fundamental tradeoff and the robustness of the network behavior is at the heart of all strategies and control mechanisms to dynamically allocate resources in the network.

The dynamic resource allocation strategies span all the layers, components and network elements in the network architecture and include, for example, dynamic voltage and frequency scaling at the component and chip level, rate adaptation and sleep modes of processors and dynamic buffer management. These technologies are effective for managing the power consumption of the network elements. Additional technologies need to be investigated to manage the power consumption at the network level from an end-to-end perspective. We now discuss some of these research areas:

New techniques are needed to reduce the energy consumption of core network routers focusing on memory storage (i.e. buffering) operations. Today's routers have gigabytes of packet buffers, which are idle much of the time and put to use only during transient periods of high loads. Progress is needed to characterize the energy consumed by always-on buffers in today's routers; characterize the usage of storage elements at each level of the buffer hierarchy (on-chip and off-chip cache/main-memory); and investigate the feasibility of dynamically turning memory elements on/off to reduce energy consumption without affecting traffic loss/throughput performance.

Currently, networks are about two to five times over-provisioned to maintain quality of service (QoS) and handle traffic spikes. This leads to increased power consumption, which can be reduced (while maintaining QoS) by optimizing the resource allocation in real-time based on demand. A good technique is using dynamic bandwidth allocation that dynamically adjusts the link bandwidth based on the measured traffic load. Traffic shaping and grooming at the edge of the network may prove to be essential in reducing the traffic peaks facilitating a smoother operation of the network at reduced total power consumption. Of course, traffic shaping cannot impact the quality of experience and research needs to be conducted to understand the trade-off between traffic engineering, quality of service and any potential energy efficiency gains.

The network's optimum resource allocation can be partitioned into three interlinked time frames. On the longest time frame, use of static mixed integer linear programming (MILP) can determine the optimum resources (e.g. number of fibers, link capacities, number of ports and routers, location of routers and switches, etc) in the network for a given traffic profile and QoS requirements. On a slightly shorter time scale, new traffic engineering algorithms can optimize energy savings and resource allocation. Finally, in the shortest of time scales optimum routing algorithms and heuristics can be applied for further energy savings. What is often missing, however, is an "all time scales end-to-end" approach to optimize resource allocation for energy saving in networks.

Telecommunication network failures usually occur with accidentally cut fiber. These occur at a rate of about 4.39 cuts/year/1,000 sheath-miles (outside plant cable distance), which equates to about one cut per day in a large operator network made up of 100,000 miles of fiber cables. In a network like this, protection resources are powered all year but used just one day in the year. Significant power savings may be attained if the protection routes are powered down. Dynamic control protocols are needed to switch off (or put into low power mode for fast re-activation) shared and dedicated protection paths until a failure is detected. Again here an "all time scales end-to-end" approach is needed for the optimum allocation of protection resources and paths that meet the required Quality of Resilience (QoR) and QoS – and minimize the power consumption.

5. Power utilization efficiency:

In order to improve the overall energy efficiency of network equipment, a holistic approach needs to consider the power consumption overhead associated with the power supplies and the cooling of the equipment. Depending on the equipment and its geographic location, about 30-50% of the total power consumption is reserved for cooling and overhead. Advances are needed in more efficient power supplies, more efficient delivery of power to the network equipment and more efficient thermal management and cooling of the equipment. Research into passive cooling or dynamically configured active cooling is expected to yield substantial gains.

It should be noted that research in improved power utilization efficiency is essential to all elements of the network and is not specific to the core network equipment. However, particular solutions need to be developed that are optimized and integrated with the core network equipment (e.g. routers, switches, cross-connects, etc.) for maximum efficiency.

The research challenges and focus areas described above are categorized into algorithms, protocols, system design, experimental studies, and enabling resources and listed below.

Optimized IP Network Architecture Research Challenges and Focus Areas

Algorithms/Protocols/System Design	Experimental Studies	Enabling Resources
•Architectures, topologies, and joint IP-optical design •Energy efficient content routing (content router design, protocols and content placement and replacement algorithms) •Scalable and energy efficient router architectures for peta-bit routers •Simplified and energy efficient protocols to eliminate unnecessary and redundant packet processing, energy efficient software •Energy efficient routing •Power aware protection and restoration	•Low power electronics & photonics •Low power opto-electronic integrated circuits •Serdes to serdes transmission in the fJ/bit range for core transmission •Passive cooling and advanced thermal management techniques •Rate adaptation and sleep cycles (processors, buffers, switch fabrics, linecards, router, optical systems) •Stable wavelength reconfiguration for optical protection and restoration	•Models for energy use in routing, switching, and transport systems •Cross-layer simulation tools •Models for in-network caching and service processing functions

Service Energy Aware Sustainable Optical Network Architecture (SEASON)

In addition to traditional IP over WDM network architectures, more disruptive and clean-slate approaches can be considered that target substantial energy efficiency gains, although in a much longer time horizon. Service centric architectures such as the Service Energy Aware Sustainable Optical Network (SEASON) architecture are particularly promising in this respect. Focusing on the requirements for different categories of services, e.g. streaming video, large enterprise data management, or large data download operations, the communication infrastructure can be designed as a clean-slate for the particular requirements in terms of latency, bandwidth, security, or quality of service. This might include moving away from packetized data and using flow or circuit switching as dictated by the energy considerations. A final solution would include a combination of these systems efficiently integrated with traditional packet networks to enable scalable networks for future high capacity scenarios.

Several technology solutions are expected to play synergistically with this approach. In particular, efficient communication at high bandwidth is realized in the wavelength layer. Intelligently adapting the wavelength layer to serve the needs of dynamic traffic changes over short time scales and over long distances has long been problematic [21]. Particular services that are delay tolerant or involve large data transactions, however, may be well suited for a dynamic physical layer. Dynamic wavelength capabilities further enable greater use of parallel fiber infrastructure—moving to higher capacity using large cables of 10^3-10^4 fibers per cable and ultimately per link between nodes. Taking up to 100 wavelengths per fiber, wavelength counts in the 10^5-10^6 range would require dynamic powering and reconfiguration for efficient use. Greater efficiency gains might be realized, however, by leveraging the very low power WDM interconnect technologies for use in the wide area network [22]. Figure 13 shows the potential efficiency gains using dynamic wavelengths for content delivery assuming a 5 second wavelength setup time (T^0) [23], which is 2-3 orders of magnitude faster than what is possible today in core networks. The efficiency benefit depends on the relative energy per bit of the transmission gear (p^{wdm}) to the routing and switching gear (p^r).

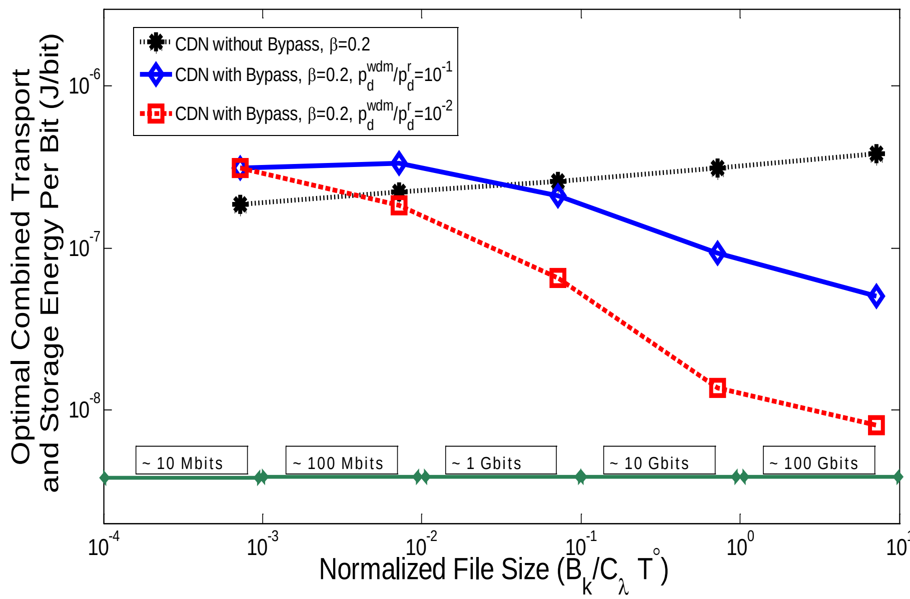


Figure 13. Optimized transport and storage energy per bit for content delivery as a function of file size comparing static networks (black, dotted) with dynamic wavelength networks for two different relative efficiencies of optical transmission (wdm) hardware and routing hardware [23].

To facilitate this service centric approach, the use of an "Application Center," which serves as the demarcation point between an access network and the core network, is considered. Application Centers accomplish two goals: (1) they are the main service delivery and management location, and (2) they serve as the nodes for a dedicated dynamic wavelength backbone network. Such centers would be expected to house both micro-data center processing capabilities for service delivery as well as the network switching and transmission equipment. Concepts such as virtual home gateway or remote MIMO processing might be implemented in these facilities. Making use of long reach PON architectures in the access would furthermore enable these Application Centers to act as a "super central office", a consolidation of multiple central offices with data center capabilities. Further benefits could be derived from using the longer reach to access facilities with a larger footprint and using state-of-the-art data center efficiency measures for these consolidated telecom offices.

Within this service centric framework, an energy cost attributed to the different service traits can be evaluated with the associated architectural trade-offs. The final architecture should be a composite of the different service specific optimizations that still achieves the desired efficiency and scalability targets. Furthermore, functionality and service characteristics that don't scale need to be identified along with their scaling functions. This understanding can be used to influence behavior and to set policy that will drive networks toward scalable solutions. One of the key issues with this architecture is that each service specific hardware or network instance must be well utilized or the composite network may be inefficient due to the accumulated common equipment/under-utilized energy load. Heterogeneous, service optimized networks must be integrated in a way that they can efficiently share the same common equipment base and overall network infrastructure. This aspect motivates a re-design of the rack and chassis architecture within telecom centers. Recent progress in high performance computing infrastructure design may be applicable here [24].

The research challenges associated with the SEASON architecture fall primarily into the experimental studies and algorithms/protocols/system design categories. Here we include those elements that are unique from the IP centric architecture. The SEASON architecture shares the research challenges and focus areas in enabling resources and the device level areas with the IP centric architecture. Due to the clean slate nature of the architecture significant far reaching problems need to be addressed. These include demonstrating service-aware dynamic physical layer functionality, transparent transmission systems in networks that support truly dynamic wavelength operation over long distances, and efficient implementations of heterogeneous-service network infrastructure. While transparent and dynamic wavelength devices and architectures have received extensive investigation, practical solutions for large scale networks have not been realized, nor has energy efficiency been a key consideration. Such capability would require a complex network scale physical layer control plane addressing power stability and cross-layer interactions. Efficient amplifier and control devices will be an integral part of the solution. At the service layer traffic management is replaced by scheduling algorithms and circuit or flow-based protocols for high bandwidth services. Novel approaches to coding include network coding or service aware combinations of source and channel coding.

SEASON Architecture Research Challenges and Focus Areas

Experimental Studies

- Demonstration of service-aware dynamic physical layer functionality in core networks
- Optical transmission networks designed to support multiple simultaneous light path provisioning and tear down events over a range of setup times limited by time of flight delay for energy and service adaptive co-design
- Efficient implementation of heterogeneous-service networks
- Low power amplifiers designed to support multiple fibers and end-to-end dynamic wavelength capability
- Integrated transceiver and wavelength circuit switching fabric operating in a core network to reduce routing infrastructure and reduce circuit switching energy/bit for targeted services

Algorithms/Protocols/System Design

- Energy aware scheduling algorithms designed for delay tolerant services that enable end to end bufferless transmission respecting QoS requirements
- Simplified and energy efficient protocols to eliminate unnecessary and redundant processing
- Energy optimized combined source and channel coding designed for end to end service dependent efficiency
- Physical layer control plane operating in the core network to provide energy optimized setup of new wavelengths, controling transmission elements and compensators to achieve stable operation

VIII. Final Remarks

This report on strategic research areas describes some of the main research challenges and focus areas identified by the GreenTouch consortium. Additional details regarding the reference network models and efficiency projections will be included in other documents for each of the respective network domains. Additional information can be found online at www.greentouch.org.

IX. Acknowledgments

The strategic research areas, research challenges, ideas, architectures, solutions and technologies presented in this document are the outcome of the GreenTouch consortium, its working groups, project teams and individual members. Special thanks are due to all the GreenTouch members for their efforts and dedication as well as for their feedback and comments on earlier drafts of this document.

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XI. Abbreviations

10GEPON: 10 Gb/s Ethernet passive optical network,
A/D: analog to digital,
ASIC: application specific integrated circuit,
BCG^2: Beyond Cellular Green Generation,
Bi-PON: bit-interleaved passive optical network,
BTS: base-station,
CDN: content distribution networks,
CMOS: complementary metal oxide semiconductor,
CPE: customer premises equipment,
CPU: central processing unit,
CROCODILE: Content Distribution and Clouds for Service Delivery,
DL: service delay,
DRAGON: Dynamic Reconfiguration Aware Green Optical Networks,
DSL: digital subscriber line,
DVFS: dynamic voltage and frequency scaling,
EE: energy efficiency,
EE HW: energy efficient hardware,
EFI-COST: Energy efFIcient high Capacity Optical OFDM Signal Transmission,
EPON: Ethernet passive optical network,
FEC: forward error correction,
FPGA: field programmable gate array,
FTTH: fibre-to-the-home,
FTTX: Fibre-to-the-X,
GPON: gigabit passive optical network,
GTT: Green Transmission Technologies,
HALF-MOON: Highly Adaptive Layer For Mesh On-off Optical Networks,
HFC: hybrid fibre coax,
ICN: information centric networks,
ICT: information and communication technologies,
IP: Internet Protocol,
LAN: local area network,
LEAN: Low Energy Access Network Architectures,
LSAS: Large-Scale Antenna Systems,
MAC: media access control,
MILP: mixed integer linear programming,
MIMO: multiple input multiple output,
NAT: network address translation,
OAM: operations, administration, and maintenance,
OFDM: orthogonal frequency division multiplexed,
OLT: optical line termination,
ONU: optical network unit,
OPERA: OPtimal End to end Resource Allocation,
PHY: physical layer,
PON: passive optical networks,
PW: power,
QoR: quality of resilience,
QoS: quality of service,
REPTILE: Router Power Measurement,

RF: radio frequency,
SCORPION: SIngle Chip Router Linecard with Integrated Photonic Interconnects,
SE: spectral efficiency,
SEASON: Service Energy Aware Sustainable Optical Network,
Serdes: serializer/deserializer,
SRA: Strategic Research Areas,
STAR: Switching and Transmission,
TCAM: ternary content addressable memory,
TDD: time division duplex,
TDM: time division multiplexing,
TV: television,
VHG: virtual home gateway,
WDM: wavelength division multiplexing,
XG-PON1: standardized ten gigabit capable passive optical network,
ZeBRA: Zero Buffer Router Architectures.